# From Theory to Practice: Rich Bottom Layer Design

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ABSTRACT: Conventional asphalt pavements are typically designed for 20-year life expectancies. To achieve more sustainable pavement structures, a rut-resistant, impermeable and wear-resistant surface course must be combined with a rut-resistant and durable intermediate layer and fatigue resistant and durable base layer. This durable base layer, referred to as a Rich Bottom Layer (RBL), is placed at the level in a flexible pavement structure where bottom-up fatigue cracking is initiated. This paper describes the application of Rich Bottom Mix (RBM) technology to the Red Hill Valley Parkway (RHVP) in Hamilton, Ontario, Canada, a new 7.5 km section of controlled access freeway, completed in 2007. It was the first example of a major urban highway where a flexible pavement was designed to last 50 years without the need for any major rehabilitation. Mechanistic analysis carried out at the pavement design stage and also actual strain measurements in the pavement monitoring system installed on the RHVP, confirm that the tensile strain in the RBL is much higher than in any of the other asphalt layers. The monitoring has confirmed that the predicted maximum tensile strains induced under standard axle loading are within the predicted range. The current pavement condition, two years after completion, is excellent. Traffic monitoring on the RHVP indicates that there is a high number of overloaded vehicles which are inducing strain levels in the RBL much higher than those from standard trucks. This situation is being monitored to evaluate whether it is likely to have any negative impact on future pavement performance. This project provided a good example of how research-level technology can begin to be applied in actual projects with the support of a forward-thinking municipality.

KEYWORDS: Perpetual pavement, rich bottom layer, fatigue.

## 1. INTRODUCTION

Over the years, most municipal governments have been forced by political pressure and scarce financial resources into a short-term approach toward pavement design and management. This has led to a cycle of acceptance of pavements that lose ride quality very quickly and need major rehabilitation every 18 to 25 years. The twenty-first century realities of excessive energy consumption, dwindling natural resources, environmental impacts of construction and the importance placed by the public on making our roads safer, rarely get factored into the analysis. In recent years, a number of enlightened road agencies in North America that deal with very high traffic volume highways have taken on this challenge of making highway design and construction more sustainable. These pioneers have begun to implement a new philosophy that recognizes that current technologies now allow us to design and build flexible pavements that can last 50 years or more without major rehabilitation.

The Red Hill Valley Parkway (RHVP) is a modern urban Expressway in the City of Hamilton, Ontario, Canada. It is the final leg of a longer Freeway project considered to be the largest municipal road project in Canada with an estimated final total cost of $430 Million. Initial opening volumes of 30,000 vehicles per day and full capacity volumes in excess of 90,000 vehicles per day were expected for this section of the City's crucial transportation artery. The 7.5 km long RHVP is located in an environmentally sensitive area of the Red Hill Creek. The City of Hamilton decided that, given the projected traffic volumes, a perpetual pavement design philosophy should be adopted.

One of the key criteria towards extending the life of a flexible pavement is to prevent the onset of fatigue failure. These materials, referred to as Rich Bottom Mixes (RBM), are placed at the level in a flexible pavement structure where the initiation of bottom-up fatigue cracking is initiated, i.e. the location where the horizontal tensile strains are highest. This paper describes the application of RBM technology to the RHVP and provides some verification of its effectiveness based on *in situ* measurements.

## 2. PERPETUAL PAVEMENT CONCEPT

Perpetual or long-life asphalt pavements are designed and constructed to provide a structure having very long useable life with a renewable asphalt surface. Essentially these pavements are designed to be totally resistant to rutting and to have a virtually infinite fatigue life. The wearing surface layer can be replaced with minimal traffic disruption. The key is to design a pavement structure that will effectively prevent bottom-up cracking.

The main components that comprise a perpetual pavement are briefly described below:

- A uniform and competent subgrade**:** As a general guide, a minimum subgrade CBR value of 5 percent should be achieved or a subgrade design resilient modulus of 50 MPa. Where marginal soils are present, lime or cement stabilization should be considered. Seasonal variations in subgrade support should be minimized by ensuring adequate drainage and sufficient subbase thickness to avoid frost heave in regions with prolonged sub-zero temperatures.
- Granular Subbase and Base Layers**:** The subbase thickness will be determined based on the mechanistic pavement design approach so as to maintain the imposed vertical subgrade strain below an acceptable level. Additional subbase thickness may be needed over and above this structural requirement in frost prone regions and based on the frost susceptibility of the subgrade soils.
- Rich Bottom Layer (RBL): The inclusion of the RBL is one of the key characteristics of a longer lasting flexible pavement. This layer, located at the transition from an unbound to a bound layer, must be fatigue resistant. For reasons of achieving an economic design, the thickness of the overlying premium asphalt layers will need to be minimized, the RBL takes on a hugely critical role in the achievement of a long lasting pavement. An effective bond must be achieved between the RBL and overlying rut-resistant asphalt layers. The RBL should also be highly resistant to intrusion of moisture rising within the substructure.
- Rut-resistant Layers: The required thickness of these layers is established from design and considering the anticipated traffic loading. These upper base layers must be rut-resistant at all in-service temperatures. They must incorporate premium aggregates,

including manufactured sand, and the appropriate Performance Graded Asphalt Cement (PGAC) grade.

- Renewable Wearing Course: The wearing course must be durable, rut-resistant, have exceptional frictional properties and have a life expectancy of at least 16 years under heavy traffic. Stone Mastic Asphalt (SMA) providing a strong stone to stone skeleton meets these requirements.

In practice, the achievement of a long lasting pavement requires the use of premium construction materials, particularly the hot mix asphalt layers. A higher emphasis also needs to be placed on the quality of construction achieved.

## 3. PAVEMENT DESIGN ANALYSIS

The RHVP pavement was designed for a traffic loading of 90 million Equivalent Single Axle Loads (ESAL's) over a 50 year design life. The structural design was performed using the AASHTO 1993 pavement design methodology (AASHTO, 1993) and verified using mechanistic-based methodologies, including the PerRoad software program (Timm, 2004). The pavement structure selected consisted of a 40 mm SMA surface course, a 50 mm Superpave 19.0 upper binder course, a 70 mm Superpave 25.0 lower binder course, a 80 mm Rich Bottom Mix (RBM) layer, 150 mm of granular base, and 370 mm of granular subbase. More information about the design and construction of the pavement on the RHVP is given in Uzarowski et al, 2008. Table 1 provides a comparison between the selected Perpetual Pavement design and the conventional deep strength asphalt pavement that would have been used for this section of urban highway. As noted above, the Perpetual Pavement achieves a design life of 50 years and 90 million ESALs compared to a 20 year design and about 30 million ESALs for the conventional design. The additional structure required amounted to an extra 80 mm of hot mix asphalt, offset slightly by a reduction in the granular subbase of 60 mm.

Table 1: Comparison between selected Perpetual Pavement design and conventional pavement design for the RHVP.

| **Pavement Type** | **Design Period (Years)** | **Traffic Loading (Million ESAL's)** | **Layer Thickness (mm)** | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Hot Mix Asphalt** | | | **Granular Base** | **Subbase** |
| | | | **Surface Course** | **Binder Course** | RBM | | |
| **Deep Strength** | 20 | 30 | 40 | 60<br>60 | - | 150 | 450 |
| **Perpetual** | 50 | 90 | 40 | 50<br>70 | 80 | 150 | 390 |

The combined binder course and RBL thickness was derived so that the horizontal tensile strain at the base of the RBL under a standard axle load did not exceed 70 microstrain. A 50-year life cycle cost analysis was undertaken of both options and demonstrated that the perpetual pavement strategy realised about a 9 % cost saving overall (Maher et al, 2006).


Figure 1 : Core extracted from completed main lanes of the RHVP showing position of RBM layer.

## 4. RBL DESIGN PRINCIPLES

Generally, improved resistance to fatigue can be achieved by increasing asphalt cement content and reducing air voids in the mix. However, it is also critical that the aggregates and asphalt cement used in the RBM are of adequate quality. Premium aggregates and polymer modified performance graded asphalt cement need to be used. In establishing the design requirements for the RBM, the leading agencies in the United States were contacted, including the University of California in Berkley (Carl Monismith), the National Center for Asphalt Technology (NCAT), the National Asphalt Pavement Association (NAPA) and the Asphalt Institute. The objective was to take advantage of the most up to date research with respect to perpetual pavement and RBM design.

The initial technology review suggested two concepts for RBM. One was the use of a modified Superpave 25.0 mix and the other was to modify a Superpave 19.0 mix. It was decided to adopt the modified Superpave 19.0 mix option to facilitate workability and reduce the potential for segregation. In keeping with the extended design life, the mix would be designed for the highest traffic category. Once the basic mix type was selected, then there were two accepted approaches for achieving enhanced fatigue performance. One is to simply design the RBM at 4% air voids and then add an extra 0.5% asphalt cement to provide resistance to the development of micro-cracking. An alternative is to include the extra 0.5 % asphalt cement and then design for 3% air voids. The former approach was adopted since there was some good documented experience with this approach. Initially PGAC 64-28 was selected for the mix but this was subsequently changed as detailed later. The above was the basis for the RBM design, however the mechanistic properties of the trial mixes would be confirmed and further adjustments made where deemed necessary to optimise the mix properties.

## 5. RBM SPECIFICATION

A project-specific specification was developed for the RBM. The basic mix requirements were to conform to a Superpave 19.0 mm mix. Superpave mix aggregate gradations are specified on the basis of master ranges from designated sieves through which gradations must pass. The control limits are typically placed on the maximum size, the nominal size, the 2.36 mm and 0.75 mm sieve sizes. Table 2 lists the aggregate gradation control points for the RBM

Table 2: Aggregate Gradation Control Points for RBM.

| **Sieve Size (mm)** | **Nominal Maximum Aggregate Size – Control Points (Percent Passing)** | |
|---|---|---|
| | **RBM – Superpave 19.0 Mix** | |
| | **Minimum** | **Maximum** |
| 25.0 | 100 | - |
| 19.0 | 90 | 100 |
| 12.5 | - | 90 |
| 2.36 | 23 | 49 |
| 0.075 | 2 | 8 |

It was also specified that the RBM mix properties, compactive effort and the aggregate properties should conform to the requirements for Traffic Category E (OPSS, 2004). This is the highest category of traffic used in design and represents projected design traffic in excess of 30 million ESALs and is used for freeways and major arterial roads. The compaction parameters for $N_{initial}$, $N_{design}$ and for $N_{max}$ (OPSS, 2004, AASHTO, 2001) were defined as shown in Table 3 corresponding to Traffic Category E.

Table 3: Compactive effort for RBM specified as Traffic Category E.

| **Traffic Category** | **Compaction parameters** | | |
|---|---|---|---|
| | $\mathbf{N_{initial}}$ | $\mathbf{N_{design}}$ | $\mathbf{N_{max}}$ |
| E | 9 | 125 | 205 |

The RBM was to be designed using the procedure described in AASHTO PP28 standard (AASHTO, 2001) and on the basis of 4.0 % air void criteria. The key modification to the standard Superpave 19.0 mix-design to achieve greater fatigue resistance was to increase the asphalt cement content. It was considered that an increase of 0.5% of the asphalt cement from that required for the conventional Superpave 19.0 mix design would achieve the appropriate fatigue resistance without unduly compromising the rut-resistance of the mix. This modified Superpave 19.0 mix design with its adjusted volumetric properties was to be used as the Job Mix formula (JMF) for the RBM.

## 6. RBM DESIGN VERIFICATION

The mix used for the RBL comprised an increased asphalt cement content and reduced air voids from a conventional Superpave 19.0 mix. As this was the first application of this type of RBM for a major road project in Canada, numerous trials were carried out to confirm and refine mix performance. Table 4 lists the range of mix testing performed.

Table 4: Summary of mix performance testing program.

| **Mechanistic Property** | **Standard** | **Specified Limit** |
|---|---|---|
| Dynamic Modulus | AASHTO TP62-03 | N/A |
| Rutting Resistance | | |
| Asphalt Pavement Analyzer | AASHTO TP63-03 | Max 5.0 mm after 8,000 cycles |
| Hamburg Wheel Rut Tester | Colorado L5112 Standard | Max 4.0 mm after 10,000 passes and max 10.0mm after 20,000 passes |
| Fatigue Endurance | AASHTO TP8-94 | Min 7 million repetitions |

The APA is used for accelerated performance testing of asphalt mixes. Pneumatic cylinders apply a repetitive load through a pressurized rubber hose to generate contact pressures representative of field loading conditions. The rut resistance of the RBM trial mix was assessed by testing briquettes in accordance with the AASHTO TP 63-03 standard. A test temperature of 58$^{o}$C was adopted for the testing and a load of 445 N was applied to each wheel during the 8,000 load cycles. The measured rut depth is shown in Figure 2. The accumulated permanent deformation was less than the 5 mm set in the specification.

The RBM while exhibiting excellent resistance to rutting, failed to meet the required repetitions in the fatigue test noted in Table 4 when tested in the four-point bending beam apparatus at higher air voids level and higher strain than anticipated in the field. Difficulties were encountered in getting additional fatigue testing performed so it was decided to adjust the mix by utilizing an asphalt cement containing a minimum of 5% polymer. As a result, the specified asphalt cement was changed from PGAC 64-28 to PGAC 70-28 to achieve an acceptable polymer content and improved fatigue resistance. In addition, the allowable field air voids in the mix were to be maintained below 3%. The mix already had 0.5% more asphalt cement than that required for Superpave 19.0.

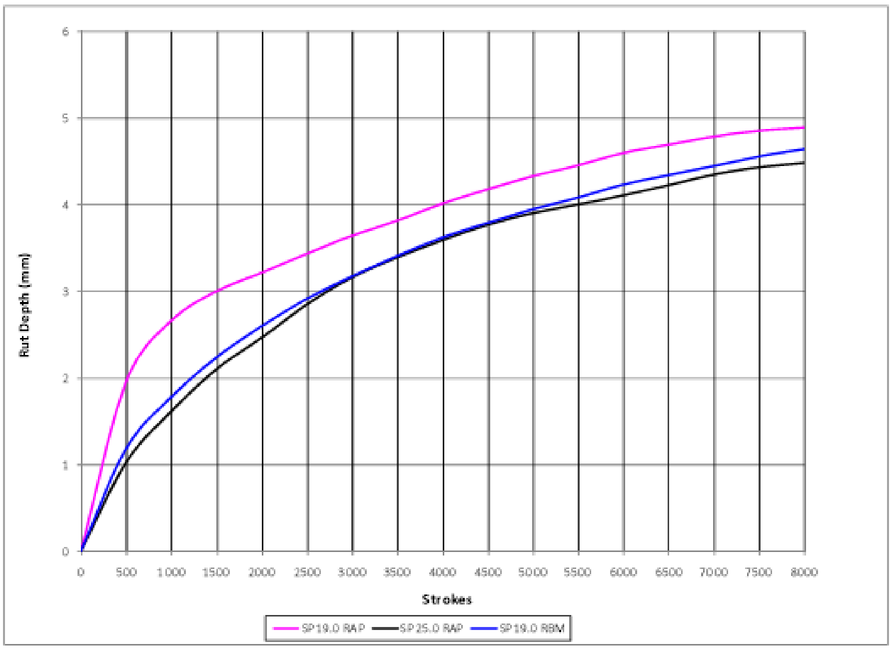


Figure 2: Plot of rut depth from APA testing showing that the RBM (blue line) sustained 4.6 mm of rutting after 8,000 load cycles.

The selected asphalt cement was also subjected to a series of acceptance and characterization tests including Dynamic Shear Rheometer (DSR), Brookfield viscosity, Bending Beam Rheometer (BBR), Creep stiffness and Flash point testing.

## 7. PLACEMENT OF THE RBL

Prior to full scale paving, a test strip was paved to verify that the requirements of the JMF could be achieved. Extensive testing was undertaken on the trial strip mix and confirmed that the RBM was within the specification requirements. The main initial concerns during construction related to asphalt check cracking, compaction and construction methodology. A cooperative team approach allowed these issues to be quickly resolved.

Check cracking was observed initially during the paving of the RBM layer. As the designed mix was on the fine limit of the grading limits, it was agreed that some mix adjustments were necessary. Thus the coarse aggregate content was increased by about 2 percent and the sand content was reduced by the same amount, the issue of check cracking was resolved. Figure 3 shows the mat free of any check cracking after the gradation adjustment.

The compaction requirements set on this project were tighter than on conventional asphalt paving projects in Ontario. The compaction was generally achieved by using increased number of rollers (6 rollers were used for the SMA wearing course, for instance), careful control of the mix temperature during compaction, and following an effective compaction operation procedure such as keeping the rollers close to paver screeds and avoiding excessive water, etc. Paving in echelon using a Shuttle Buggy® material transfer vehicle (MTV) contributed to the successful achievement of the compaction requirements, mitigated problems with longitudinal joints and eliminated any potential for gradation or thermal segregation. The mix surface achieved had a tight texture and had an appearance of a rich mix.

Originally, it was intended to limit construction traffic on the surface of the RBM to the paver and rollers. Given the observed performance of the RBM and the desire to pave the overlying Superpave 25.0 layer in echelon, it was decided to allow limited construction traffic on the surface of the RBM layer. This facilitated paving of the Superpave 25.0 and avoided construction of longitudinal joints in this layer. However, the length of the RBM opened to the hot mix delivery trucks was limited to 300 m and the number of trucks allowed to wait in front of the paver was also limited to a maximum of three.


Figure 3: RBM layer after adjustments to the aggregate gradation.

The *in situ* density achieved in the RBL was confirmed by measurements using a nuclear density gauge calibrated against core densities. The target was to achieve 97 percent of the maximum relative density of the mix which ranged from 2,522 kg/m$^3$ to 2,532 kg/m$^3$.

## 8. IN SITU PERFORMANCE

To verify the performance of the pavement materials in the RHVP and to confirm the perpetual pavement design, the City of Hamilton opted to install a pavement response system. This system included pressure and moisture gauges in the subgrade, asphalt strain gauges in the RBM, Superpave 25 and SMA layers and temperature sensors in the subgrade, granular and asphalt layers.

A traffic monitoring system comprising traffic loops and weigh-in-motion (WIM) sensors were also installed in the RHVP. The traffic data is synchronized with the pavement response data allows for the analysis of the strains in the pavement and also the relationship with the induced stresses and loads causing these strains. The pavement on the RHVP was anticipated to initially carry a traffic volume of about 30,000 AADT increasing over time to about 90,000 AADT in Year 50. The data from the traffic system recently indicated that about 34 million vehicles have used the RHVP since the opening in November 2007. Soon after opening, the traffic volumes were at 35,000 vehicles per day, while in June 2009 the volumes had increased to over 60,000 vehicles per day.

Figure 4: Longitudinal and transverse strain gauges installed in the RBM layer.

The temperature sensors showed that the measured RBM temperature was higher than the air temperature by 2°C to 10°C. The strains were measured in both the longitudinal and transverse direction in the RBM. Figure 5 shows the wheel load versus strain in the RBM layer. The transverse strain in the RBM is proportional to the applied load and the relationship is good with $R^2$ of 0.79. For the standard wheel load of 40 kN, the strain in the RBM was about 28 microstrain. Mechanistic analysis carried out at the pavement design stage and also actual strain measurements in the pavement monitoring system installed on the RHVP, clearly show that the tensile strain in the RBL is much higher than in any of the other asphalt layers. The monitoring has confirmed that the predicted maximum tensile strains induced under standard axle loading are within the predicted range.

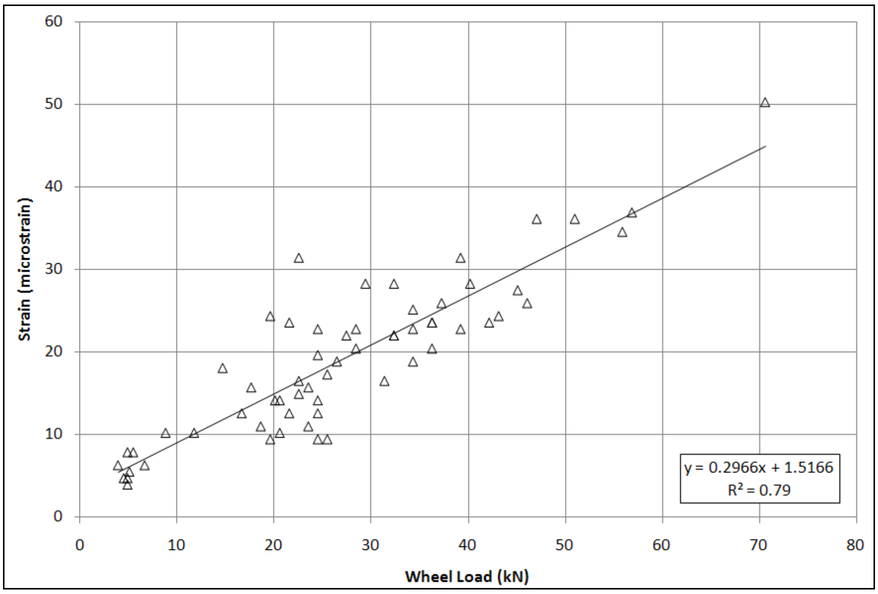


Figure 5: Wheel load versus strain in the RBM layer

The current pavement condition, two years after completion, is excellent. Traffic monitoring on the RHVP indicates that there is a high number of very significantly overloaded vehicles which are inducing strain levels in the RBL much higher than those induced by standard trucks. This situation is being monitored to evaluate whether it is likely to have any negative impact on future pavement performance.


Figure 6: Completed section of RHVP.

## 9. CONCLUSIONS

This paper documents the application of the perpetual pavement design concept for a major urban highway in Southern Ontario. It focuses on the Rich Bottom Mix layer within that pavement, one of the key components contributing to the extended serviceable life. The paper documents the design and mix verification process for the RBM and provides early feedback on the performance of the RBM layer based on analysis of instrumentation embedded in the roadway. The main conclusions from this work related to the design and performance of RBM are as follows:

- A modified Superpave 19.0 mm mix provides a practical basis for RBM.
- The standard adopted for establishing the fatigue resistance in the laboratory may be overly demanding and further research is needed to refine the laboratory-derived fatigue requirements.
- Given the critical nature of this major piece of road infrastructure, a conservative approach was taken to the development of the RBM, including the use of a heavily polymer modified asphalt cement.
- Even with extensive laboratory mix development and verification, the role of quality assurance inspection and testing during the paving operations were key components to achieving the successful outcomes.
- The *in situ* monitoring has confirmed that the projected critical tensile strains in the RBM were not exceeded under design loading. However, the impact of overloaded axles has been shown to lead to much higher tensile strains. While we are confident that this will not compromise the projected design life, this issue needs further investigation and mitigation.
- This project provided a good example of how research-level technology can begin to be applied in actual projects with the support of a forward-thinking municipality.

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